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A review of harmful algal blooms (HABs) and their potential impacts on desalination facilities

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ABSTRACT

Arid countries throughout the world are massively reliant on seawater desalination for their supply of drinking and municipal water. Harmful algal bloom (HABs), frequently referred to as 'red tides' due to their vibrant colors are predicted to grow in recurrence and distribution in the coming years where numerous desalination facilities will become increasingly susceptible to damage or shutdown during HAB events. Such a phenomenon, one of the operational challenges facing the industry, can cause significant operational issues that result in increased chemical consumption, increased membrane fouling rates, and in extreme cases, a plant to be taken off-line due to the high biomass of microalgae and a variety of substances that some of these algae produce. Hence, understanding the HABs' nature, their challenges, and ways in which they can be monitored, treated, and mitigated will allow engineers and operators to address HAB hazards and maintain the integrity of new and existing desalination facilities.

Keywords: Desalination; Harmful algal bloom; Red tide; Algal toxins; Dissolved air flotation

1. Introduction

The increasing demand for fresh water in many areas in the world is due to drought, water shortages, an increase in population, and the high-quality drinking water desire [1]. Water shortages have been for a long time a significant problem in the Middle East [2]. This area is considered the world's most water-scarce region. The lack of natural freshwater supply for domestic purposes is more critical for the Arabian Peninsula countries, including Saudi Arabia, where the water demand increases annually by 3% or more; however, groundwater supply limitation has led such a country to become increasingly dependent on desalination to provide an adequate supply of freshwater; hence became the global leader in the development as well as the use of desalination technologies [3]. More generally, desalination refers to the removal of salts from seawater turning it into safe potable or usable water [4]. In recent, some natural events, such as algal blooms or red tides become more pervasive which may generate operational problems for coastal seawater desalination facilities [1].

Due to the sea surface discoloration, "red tide" is a common term used for harmful algal blooms (HABs) [5]. This discoloration from red (red tides) to yellow, green, brown, or blue is dependent on the type of algae and its depth and concentration [6]. HABs are a phenomenon in which the numbers of photosynthetic marine organisms grow suddenly and rapidly beyond typical ambient levels, posing serious threats to human health, natural resources, and coastal facilities [7]. Such a phenomenon is induced

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by climatic and hydrographic conditions, including seasonal temperature changes, an abundance of sunlight and anthropogenic activity [6,8]. Photosynthetic, single-celled organisms depend on light and nutrients, such as iron, phosphate, and nitrogen to grow and multiply [7]. The duration of the algal bloom event may last for a period of a few days to several months depending on various factors, such as causative species life cycle, the environmental condition and the availability of nutrients [8].

Practically every coastal country worldwide can be affected by the harmful blooms of microscopic algae or phytoplankton and might have a severe impact on coastal desalination facilities, which could pose a threat in countries relying mainly on such plants for their water supply. The algal blooms threats on the desalination plants started to gain more increased attention during the catastrophic 2008–2009 red tide bloom in the Arabian Gulf, which forced numerous plants to reduce or entirely shutdown operations [9]. Seawater desalination plants in Saudi Arabia have experienced some of the worst HAB outbreaks; however, the recent incidents of such blooms were reported on August 2021, near the Shuqaiq desalination plant intake, located on the coast of the Red Sea, causing fish kills accompanied by surface seawater discoloration (reddish-brown color) and odor [10]. As a consequence, the desalination facilities were forced to shutdown where the entire production in the Shuqaiq production system (reverse osmosis) was suspended along with a production decrease in the desalination plant of the Shuqaiq Water and Electricity Company due to clogging of pre-treatment systems and/or unacceptable reverse osmosis (RO) feedwater quality (high rates of silt density index SDI) that might lead to irreversible RO membranes fouling. The overall decline was about 28% of the total daily production, which led to a 30% reduction of the water pumping amount to the Asir and Jazan regions.

The purpose of this article is to provide an overview of HABs, including their basic characteristics and factors that influence their generation and to highlight the negative effects of the red tide on seawater desalination plants' operation and their impact on the quality and safety of the product water and also to outline the most effective prevention and protection strategies and techniques for red tide detection and mitigating their adverse impacts on desalination facilities.

2. Desalination technology

Desalination is a process in which freshwater is separated from brackish water or saltwater. Desalination technologies provide a sustainable water source to meet water demands in areas where drinking water would otherwise be an issue. Such technologies involve two major categories which are largely used for desalination; thermal and membrane-based technology (Fig. 1) [4]. The historical and future growth operating capability (in million m^3/d) with regards to desalination technology and regions is shown in Figs. 2 and 3 [11].

Thermal desalination is the simplest procedure of desalination by phase separation of water at the boiling point at very low pressure and is mainly applied in oil-rich countries of the Middle East, while reverse osmosis (RO) membrane system, pressure-driven and electrical energy, is used for pumping water at high pressure utilizing semi-permeable membranes to remove salts while allowing pure water to

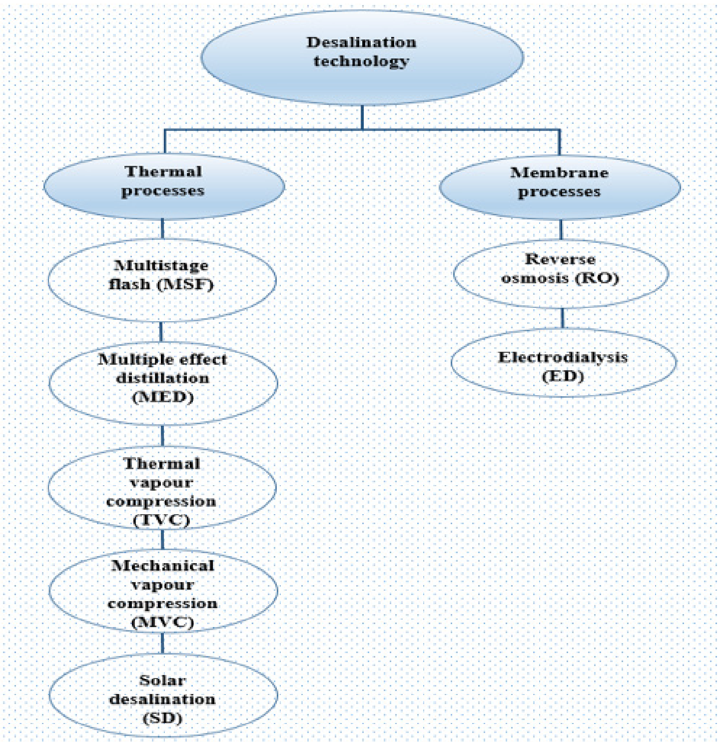

Fig. 1. Classification of the desalination process. Information based on Gude [12].

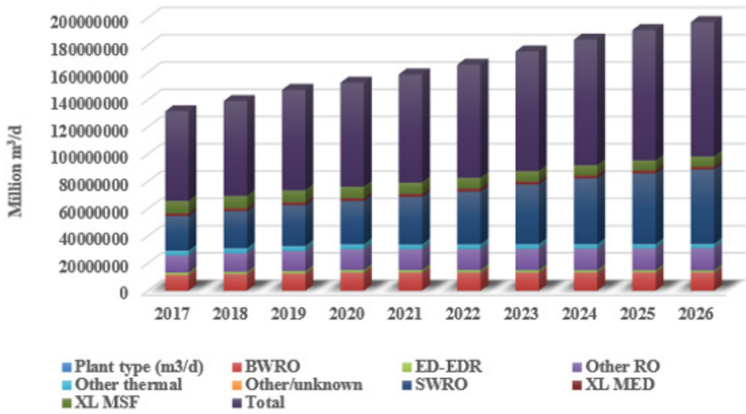

Fig. 2. Historical and future increase in the operating capacity (in million m^3/d) with regards to desalination technology. Primary data from [11].

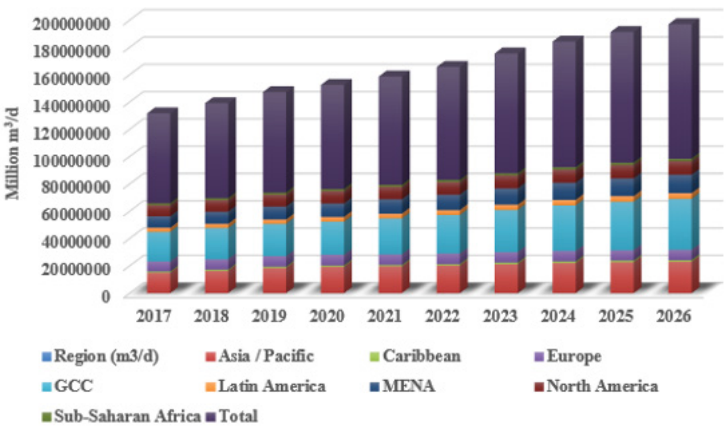

Fig. 3. Historical and future increase in the operating capacity (in million m^3/d) with regards to regions. Primary data from [11].

pass through and almost exclusively used in the rest of the world (Figs. 4 and 5) [1,8]. Over time, the cost reduction of membrane-based desalination has enabled many countries to implement this system for water supply; thus, the global reverse osmosis capacity is continuously growing steadily [13]. Currently, such a system has the largest total capacity compared to other processes and accounts for about 65% of the total global desalination capacity [1,13,14]. A summary of the main features of these processes is summarized in Table 1.

3. Marine algal blooms

Aquatic environments, such as oceans, rivers, lakes, and streams often overflow with microscopic plants called algae that can capture the sunlight energy with their pigments to grow and propagate near the water's surface. The increasing abundance of such microscopic organisms over background levels is termed "blooms", analogous to a flourishing growth of aquatic plants. Algal blooms can range from dilute cell concentrations to dense accumulation that generally discolors the water appearance. Most of the algal species are non-motile whereas others are motile; however, the motion of waves, currents, and tides can determine the distribution of such species. Phytoplankton (floating or swimming marine algae), the microscopic algae, are important primary producers and critical to life on earth, as they take in carbon dioxide (CO_2) and produce half of the oxygen (O_2) we breathe and represent the base of the aquatic food chain. Most algal blooms are natural and necessary components of any marine ecosystem; however, they can have an impact on the economy and public health.

3.1. Harmful algal blooms

Some bloom-forming algal species can be harmful and might cause problems when they accumulate in sufficient numbers, due to either their toxins production or their large biomass density and algal organic matter (AOM); however, the bacterial degradation of such organic material can lead to oxygen depletion (hypoxia), causing aquatic flora and fauna mortality [9].

3.1.1. Toxic blooms

Some HAB species can release toxic substances when they are present in large quantities (blooms). Their toxins

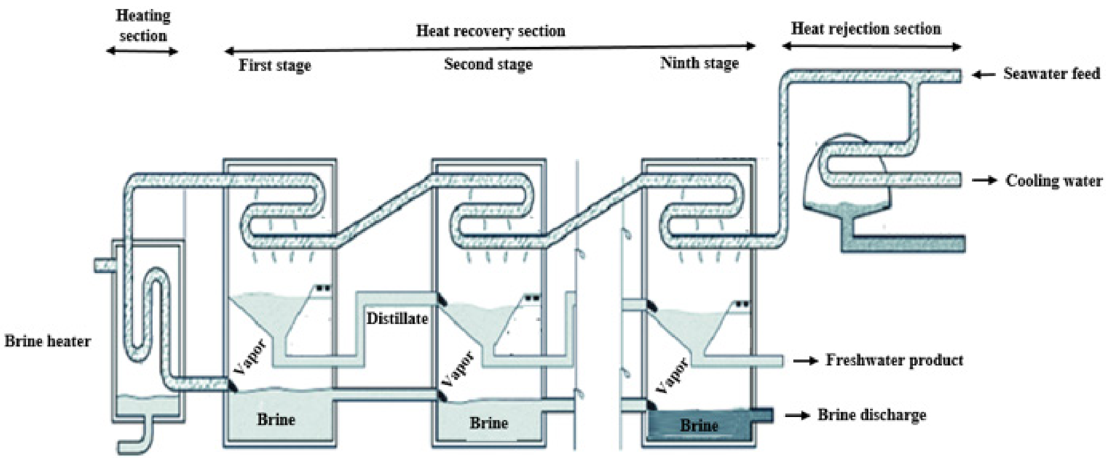

Fig. 4. An illustration of the multi-stage flash distillation (MSF) process.

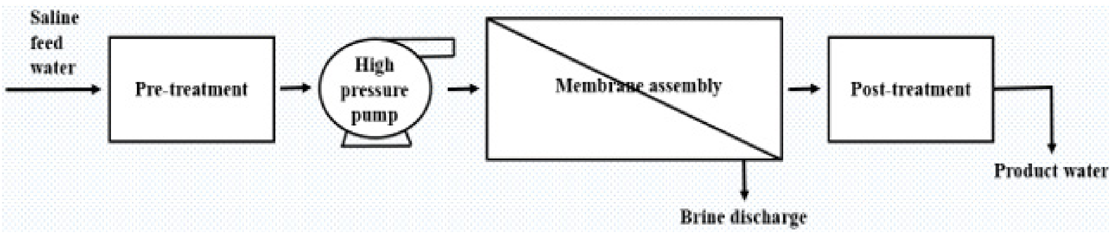

Fig. 5. An illustration of the reverse osmosis (RO) process.

Table 1
Broad classification of desalination technologies

Classification	Thermal technology	Membrane-based technology
Separation mechanism	Phase change	Diffusion
Energy requirement	Thermal	Electricity
Driving force	Heat	Pressure/Electricity
Energy consumption	High	Low

Information based on Woo et al. [15].

are among the most powerful natural poisons known. Toxic species are normally existing in low densities with no environmental or human health influences; however, at high cell density, they can be ingested by filter-feeding shellfish, zooplankton, and herbivorous fishes, leading to bioaccumulation and biomagnification of toxic chemicals in various organisms at each trophic level of the food chain, causing multiple adverse impacts [16]. The algal toxin has been reported to be responsible for more than 50,000 intoxication incidents per year, with an overall death rate of 1.5% on a worldwide scale [17]. Toxin-producing algal species can influence ecosystems and can have severe food chain impacts, including human poisonings. Such species are most commonly found in a diversity of algal classes: *Dinophyceae* (dinoflagellates), *Bacillariophyceae* (diatoms), *Raphidophyceae* (raphidophytes), *Prymnesiophyceae* (prymnesiophytes) and cyanobacteria (blue-green algae) [18]. Concerning *Prymnesiophyceae*, the dangerous members can be found in the genera *Prymnesium*, *Chrysochromulina* and *Phaeocystis* [19]. The toxins in these species can act as a defense strategy against different organisms or as a tool for space completion; however, mass fish deaths can be triggered by HAB [20]. However, the major classes of naturally occurring marine biotoxins are paralytic shellfish poisoning (PSP), diarrhetic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), azaspiracid shellfish poisoning (AZP) and neurotoxic shellfish poisoning (NSP) (Table 2) [21].

3.1.2. Non-toxic blooms

Due to the high biomass of the algal blooms, non-toxic HABs might have also an impact on marine ecosystems, fisheries resources, and commercial and recreational facilities [22]. Also, when the algal bloom enters the termination stages and starts to decay, oxygen can be consumed, causing extensive deaths to all plants and animals in the affected area [9]. The most frequently reported types of bloom-forming

Table 2
Classification of common marine HAB biotoxins

Marine biotoxin	Group	Source
Saxitoxin	Paralytic shellfish poisoning (PSP)	*Alexandrium* spp., *Gymnodinium catenatum*, *Pyrodinium bahamense*, *Anabaena* spp., *Anabaena* spp., *Aphanizomenon* spp., *Cylindrospermopsis* spp., *Lyngbya* spp., *Planktothrix* spp.
Yessotoxin Okadaic acid Pectenotoxin	Diarrhetic shellfish poisoning (DSP)	*Protoceratium reticulatum*, *Lingulodinium polyedrum*, *Gonyaulax spinifera*, *Dinophysis* spp., *Prorocentrum lima*
Domoic acid	Amnesic shellfish poisoning (ASP)	*Pseudo-nitzschia* spp., *Nitzschia* spp., *Nitzschia navis-varingica*, *Chondria armata*
Brevetoxin	Neurotoxic shellfish poisoning (NSP)	*Karenia brevis*, *Chattonella verruculosa*, *Karenia brevisculcatum*, *Karenia selliformis*, *Karenia papilionacea*, *Karenia mikimotoi*
Azaspiracid	Azaspiracid shellfish poisoning (AZP)	*Azadinium spinosum*, *Amphidoma languida*

Information based on Villacorte et al. [8] and Visciano et al. [23].

species of microscopic algae and cyanobacteria (blue-green algae) are shown in Table 3.

3.1.3. Macro-algal blooms

Over the past few decades, blooming macroalgae, such as seaweeds have substantially increased along the coastal shoreline. They are produced by estuarine nutrient enrichment in which the ocean floor lies within the photic zone [24]. Such blooms have a wide range of environmental influences and often persist longer than "typical" phytoplankton HABs [25].

3.2. Algal organic matter

Natural organic matter (NOM) can be defined as a mixture of multiple organic compounds that are globally present in natural waters [26]. Such compounds originate from both autochthonous (local input) and allochthonous (external input) sources; however, algae are a primary source of autochthonous NOM (or algogenic) organic matter (AOM) in the Earth's oceans [8]. In aquatic environments, algal species secrete the AOM as a by-product during photosynthesis from a secondary metabolism. Algal blooms (harmful or non-harmful) generate different kinds and differing levels of AOM composing essentially biopolymers, such as polysaccharides, proteins, nucleic acids, lipids and small molecules [8,27]. AOM comprises both extracellular organic matter (EOM) that is released during the metabolic activity and intracellular organic matter (IOM) or cellular organic matter (COM) when cell lysis occurs [28]. However, EOMs consist mainly of polysaccharides and tend to be hydrophilic whereas IOMs (COMs) that contain proteins tend to be hydrophobic [8,29].

3.3. Transparent exopolymer particles

In the marine ecosystem, transparent exopolymer particles (TEP), one of the organic substances found in seawater, is produced by algae and bacteria as an extracellular secretion. They can be formed from dissolved organic matter (DOM) directly through the biotic pathway where some bacteria and microalgae (e.g., phytoplankton) produce them or indirectly through an abiotic pathway from precursor particles such as polysaccharides fibrils secreted by bacteria and phytoplankton [30].

4. Harmful algal blooms and desalination facilities

The coastal areas around the seawater desalination plants are becoming more important as a source of drinking water [13]. Over the years, it is becoming more evident that microscopic algae are a primary cause of operational problems to coastal desalination plants [8,9]. Such microbes can also have an impact on adequate and safe drinking water supplies [6,20]. There are two possible influences of algal blooms on desalination facilities; significant treatment challenges to ensure that desalination systems are effectively removing algal toxins from seawater and operational difficulties due to the increased total suspended solids and organic loading resulting from algal biomass in the raw seawater [31].

During the event of algal blooms, an improvement in algal growth might often lead to an increase in the total suspended solids (TSS), total organic carbon (TOC), and taste and odor compounds resulting from biomass growth [7]. However, the total suspended solids are generally used to indicate the possibility of the intake bay becoming a source of elevated silt density index (SDI) for seawater desalination plants [1]. Such an algal growth might cause serious operational problems in desalination plants, including rapid clogging and poor effluent quality of the pre-treatment system and may force the facility to be shutdown to protect the downstream processes and to avoid further damages [8,9].

Seawater reverse osmosis (SWRO) system is more sensitive to source water quality and the pretreatment of such a process plays an essential role in terms of ensuring constant water quality before the RO stage. Algal organic matter (AOM), a fraction of dissolved organic matter (DOC) found in seawater, has been shown to be a major concern that might lead to organic and biofouling in RO plants

Table 3
Bloom-forming species of microscopic algae and cyanobacteria (blue-green algae)

Group	Bloom-forming species	Potential impacts on the marine ecosystem
Dinoflagellates	*Alexandrium* spp.	Toxins
	Cochlodinium polykrikoides	Toxins, hypoxia
	Karenia brevis	Toxins, hypoxia
	Noctiluca scintillans	Hypoxia
	Prorocentrum spp.	Hypoxia
Diatoms	*Chaetoceros* spp.	Hypoxia
	Pseudo-nitzschia spp.	Toxins, hypoxia
	Skeletonema costatum	Hypoxia
	Thalassiosira spp.	Hypoxia
Haptophytes	*Emiliania huxleyi*	Hypoxia
	Phaeocystis spp.	Hypoxia
Raphidophytes	*Chattonella* spp.	Toxins, hypoxia
	Heterosigma akashiwo	Toxins, hypoxia
Cyanobacteria	*Nodularia* spp.	Toxins, hypoxia

Information based on Villacorte et al. [8].

[32,33]. Release of such organic matter during the algal blooming either from the natural death cycles or through shear in the pumping system can be a challenge for water treatment plant operators due to algal cells scum formation during flocculation and accumulation on the surface of the media filter. Floating sludge or scum accumulation on top of the media filtration might cause the media filtration to be stopped within 10–12 h and reduce the water filtration capacity; thus, affecting the availability of RO feedwater. Besides, such formation and accumulation might lead to a filthy smell, increase the SDI value to above 5 (typically less than 3 based on the membrane type) at both inlet and outlet of cartridge filter and may pass through the pretreatment system to the RO process. However, excessive intensity and algal bloom duration might overwhelm the SWRO pretreatment system forcing the plant to be shutdown.

As the algal bloom life cycle peaks and decays, a significant quantity of organic material can also be released upon cell death; however, bacteria can feed on the decaying material (nonliving organic matter) and excrete extracellular polymeric substances (EPS) that are likely to escape pretreatment and foul the RO membranes [1]. Such decayed materials possibly have further influence on membrane fouling, the unwanted growth of biofilms on a surface, than algal cells themselves.

On the other hand, TEP has also attracted increasing attention due to its possible contribution to membrane fouling, especially in biofouling. Such transparent gel-like aggregations of polysaccharides (a very sticky substance) have been identified as a key compound that can lead to membrane biofouling [34]. In feedwater, TEP is considered to have a greater fouling propensity than other foulants due to the following distinct characteristics: (i) TEP has a higher viscosity (easily adhere to the surfaces of membranes); (ii) they are usually heavily colonized by microorganisms (serve as a conditioning layer for bacterial colonization); (iii) they are deformable (easily penetrate the small pores of the membranes) (Fig. 6) [34]. In general, the development of organic load in source water can accelerate the biofouling of RO membranes and thus could hurt the desalination plant's overall performance and efficiency. As a consequence, reverse osmosis (RO) membranes may experience particulate fouling or biofouling, and elevated energy costs due to losses in hydraulic head pressures [7].

Although the availability and output of thermal desalination can be affected, during the prolonged 2008 algal

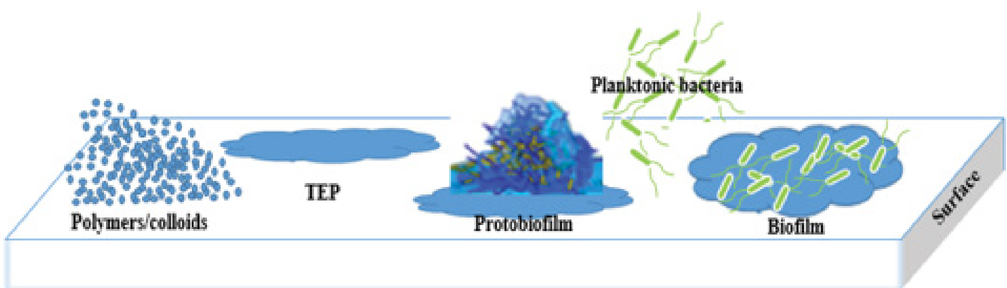

Fig. 6. Schematic diagram of the potential involvement of colloidal biopolymers, TEP and protobiofilm (suspended TEP with intense microbial growth and colonization) in the initiation of aquatic biofilms. Planktonic bacteria (first colonizers) can attach reversibly onto a surface or irreversibly on a TEP-conditioned layer. Figure and descriptions were adapted from Bar-Zeev et al. [36].

bloom in the Gulf, high concentrations of the marine dinoflagellate *Cochlodinium polykrikoides* had a limited impact on thermal plants and the multi-stage flash distillation (MSF) plants at Fujairah 1 in the UAE, continued to function without issue while the seawater reverse osmosis (SWRO) desalination plant had to be shutdown for more than one week [7,35]. In general, reduction in the desalination plant production might reach 40% during HABs events, with an influence on the desalinated drinking water quality due to taste and odor problems along with HAB toxin residues [6,20]. Fig. 7 shows the anthropogenic and environmental impacts on harmful algal blooms developments and their risks to desalination facilities.

5. Harmful algal blooms and desalinated drinking water quality

Some of the algal species may cause problems when they reach adequate numbers, due to either their toxins production or their high concentration of biomass [8,9]. Such toxic substances might lead to mortalities of marine mammals and human gastrointestinal symptoms, paralysis, and death [7]. The ability of toxins to pass through pretreatment, RO, and thermal desalination systems is not well understood; however, the charge and molecular weight of various toxins suggest that RO membranes would theoretically reject them effectively while thermal desalination facilities are expected to be less affected because of their ability to potentially degrade problematic compounds [7]. Nevertheless, the removal of the algal toxins by thermal desalination processes has not been well investigated [35].

6. Seawater reverse osmosis (SWRO) pretreatment technologies

Due to lower cost and energy consumption compared with conventional thermal distillation, reverse osmosis technology has become the dominant technology in different regions [37]. SWRO membranes are highly susceptible to changes in feedwater quality and the levels of certain organic compounds that make such membranes responsive to biofouling. Membrane fouling lowers operational performance and membranes lifespan, raising the total cost of the treatment process [38,39]. As a means of decreasing the effect of poor feedwater quality on membrane-based desalination, pretreatment processes are installed to improve the quality of raw seawater before entering a SWRO system [40]. There are different types of pretreatment processes for SWRO; primary pretreatment, consisting of coagulation and flocculation in combination with a clarification process, such as sedimentation or dissolved air flotation (DAF); and secondary pretreatment, involving the filtration system [8,9]. Algal bloom-impacted seawater can influence operational problems in SWRO compared to thermal technology, reducing the normalized flux and raising the feed channel pressure drop, leading to a substantial

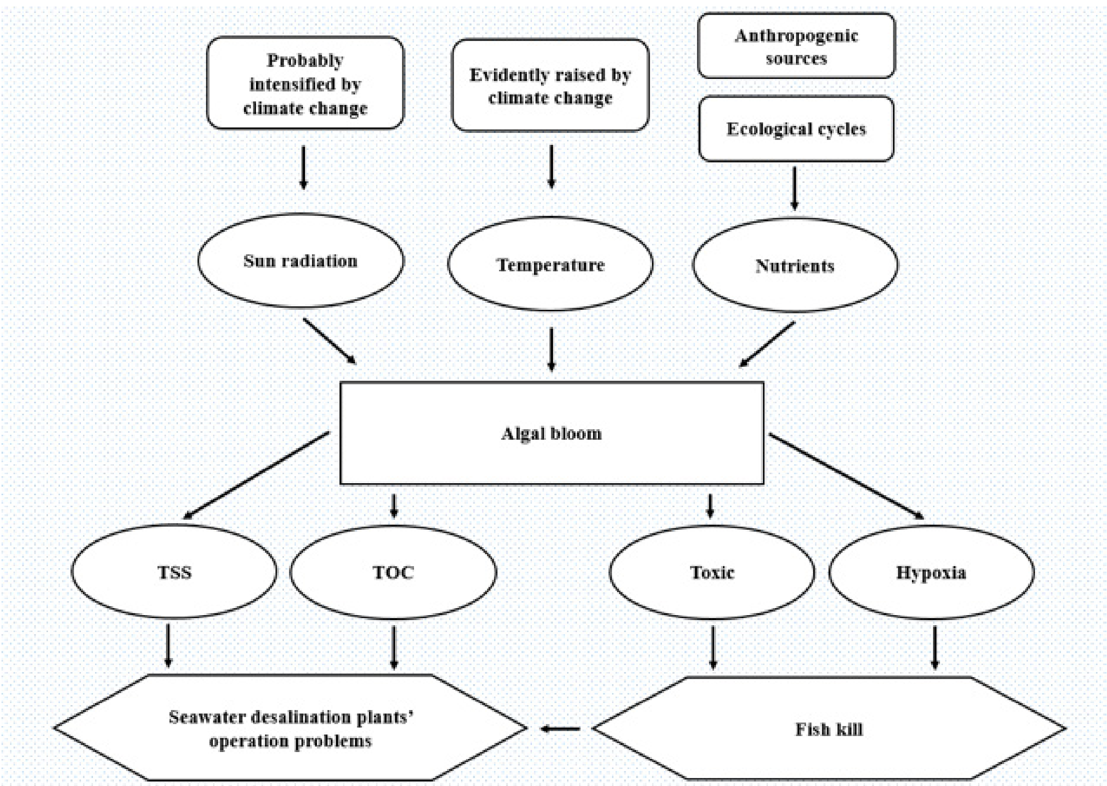

Fig. 7. Anthropogenic and environmental impacts on harmful algal blooms development and their potential influences on desalination facilities.

loss in permeability. Therefore, an appropriate selection of pretreatment, during algal blooms, is required to improve raw water quality in order to reduce damage to downstream processes and membrane fouling potential.

7. Strategies for prevention, control and mitigation of harmful algal blooms

During an algal bloom event, harmful marine algal blooms (HABs) can have a negative impact on the seawater desalination plants' operation [41]. They usually occur suddenly and without an early warning. Therefore, many technologies and strategies can be used to deal with and combat an invasive or harmful species in desalination facilities.

7.1. Detection and monitoring technologies

7.1.1. Nitrogen and Chlorophyll-a analyzers

The extreme rise in nutrients, such as nitrogen can promote and support the growth of algae causing excessive algae blooms. However, Chlorophyll-a, the primary pigment, can be found in all organisms that perform photosynthesis [42]. Therefore, a nitrogen analyzer can be applied to monitor the limiting nutrient concentrations in a water supply; thus, allowing engineers and operators to determine whether changes in detected nutrient levels may impact HABs development; whereas Chlorophyll-a analyzers, which detect light-capturing pigments being in photosynthetic organisms, can be applied to provide operators with advance warning of HABs events and enable them to improve desalination pretreatment schemes effectively in response [7].

7.1.2. Remote sensing technology

Satellite remote sensing is one of the most important techniques in the detection and tracking of algal blooms. Such a technology can be used to detect and track Chlorophyll-a as a general indicator of harmful algal blooms. Moderate Resolution Imaging Spectroradiometer (MODIS), the instrument aboard the NASA's Terra and Aqua satellites, is a satellite-based observation system that can image the entire planetary surface every one or two days, obtaining data in 36 spectral bands with wavelengths ranging from 0.4 to 14.385 μm; however, the red tide can be clearly captured using this system [43,44]. Ocean color sensors on such satellites are a valuable tool for taking measurements of the marine biosphere, covering large areas, and allowing a synoptic scene to be obtained regularly (daily revisits) [5]. During the red tides event from August 2008 to May 2009, NASA's MODIS pictures were used easily to detect and monitor Chlorophyll-a over a large area of the Arabian Gulf [1]. In the Gulf of Mexico, satellite remote sensing is used operationally to detect HABs and with simple transport models, predictions are issued of coming landfall or exposure [22]. Zhao and Ghedira [45] have shown the benefit of combing satellite observations and numerical models for studying red tide outbreaks and dynamics in the Arabian Gulf. The satellite information has also proved to be very useful for the early detection of the 2008 red tide in the Gulf of Oman and the Persian Gulf, suggesting that algorithms require improvement to accurately estimate chlorophyll-a in highly turbid water and red tide areas [46]. In the same vein, Churman and Henthorne [7] have also stated that satellite imaging technologies data should be cross-referenced with ground data for accuracy when possible. Therefore, such a system can help operators in desalination facilities plan for potential HAB events.

7.2. Desalination intake systems

The intake structures can be used to supply seawater feed to desalination plants and can provide promising protection to desalination facilities. In the desalination industry, it is more important to have a reliable intake system that can provide adequate quantities of good quality feedwater while minimizing the associated environmental impacts. Such a system that serves as part of the pretreatment system can help with environmental impacts mitigation, chemical use and operating costs of the desalination facility. In general, there are two main types of intake systems; direct and indirect intake systems (Fig. 8).

7.2.1. Direct (open water) intake system

This kind of system, known as open-ocean or shoreline intake, is the most commonly used intake type for SWRO desalination plants. The construction of this system can be along the shoreline, commonly used for power plant cooling water, or offshore (submerged), which connects the intake structure to a pipeline [47]. However, the raw seawater quality of the open-ocean intake is changeable based on the seawater quality differences around the intake point. The direct system can also be classified into either surface or deep-water intakes based on the intake pipeline depth. In surface intake systems, seawater is usually extracted from shallow water depths (1–6 m). The extracted feedwater at this depth has lesser quality due to the presence of organic content, suspended solids, and photosynthetic microbes. In deep-water intake, the seawater is obtained at depths of more than 35 m; thus, such water is generally of higher quality [48]. In general, an offshore intake terminal that extends farther and deeper into the ocean may help to avoid regions in which biomass may accumulate, as well as the seawater's photic zone, where HAB organisms tend to grow [7]. However, further protection at the pipe terminal of open-ocean intake is needed to minimize impingement and entrainment of marine life [49].

7.2.2. Indirect (subsurface) intake system

Subsurface intake systems are designed based on the riverbank filtration concept which has been used widely for the freshwater treatment of rivers in Europe and to some extent in the United States for over a century [50]. Typically, the extracted raw seawater through such systems has better quality and the complexity of the pretreatment process can also be significantly reduced. Natural filtering through subsurface intake systems can provide good treatment for feedwater before entering the desalination plant [51]. However, environmental impacts are expected to decrease as no entrainment and impingement can occur using this type of intake.

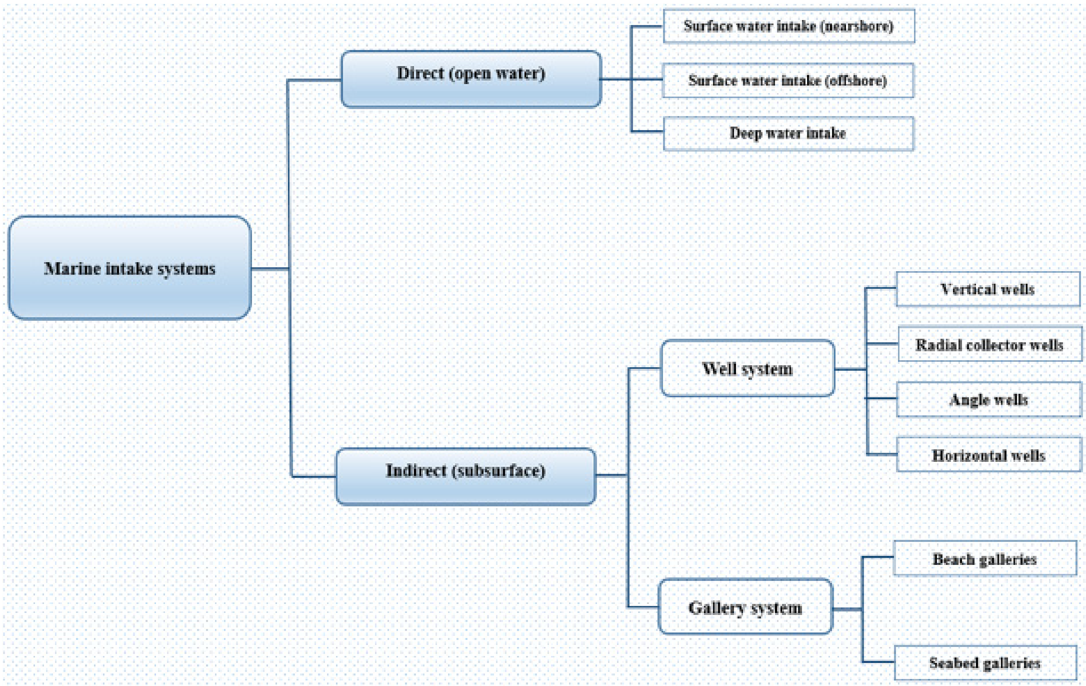

Fig. 8. Classification of intake systems.

Subsurface intake systems can be classified into wells and galleries; however, wells can be subdivided into vertical wells, Ranney/collector wells, angle (slant) wells, horizontal wells while galleries are subdivided into beach galleries and seabed filters/galleries (Figs. 9 and 10) [52]. Subsurface intakes are favorable in coastal and nearshore areas where the geological structure contains permeable rocks and a sufficient thickness of gravel and porous sand deposits underneath the coastal region. Such systems are employed in many parts of the world to supply feed to a relatively large number of desalination facilities, including Malta, Mallorca, Mexico, South America, Canary Islands, UAE, Kuwait and Caribbean Islands [53]. However, they can benefit from natural filtration and underground detention to diminish HAB organisms and their metabolic by-products accessing a seawater desalination facility [7,54]. The raw water produced from such systems ordinarily has lower concentrations of suspended solids, algae, bacteria, and NOM compared to raw seawater; thus, has a lower fouling potential [55]. As shown in Table 5, subsurface intakes are effective in removing algae, biopolymer and TEPs from different marine resources.

It is known that the capacity and performance of subsurface intake are highly dependent on the local hydrological and geological conditions at the intake site; however, well location and type are also essential to ensure a sufficient yield and the quality of the feed water quality. A study by Dehwah and Missimer [56] has shown that the geological characteristics of the offshore ocean bottom were found to be favorable for the development of seabed gallery systems, but the shoreline geology was not adequate for the development of beach gallery intakes. Such a system can be used to supply feed water for large-scale SWRO plants but the capital cost is higher since construction is performed offshore. Fukuoka seawater RO plant in Japan is the only large desalination plant that uses a seabed intake system with an intake capacity of 103,000 m^3/d [57]. Vertical wells, the most commonly used type of well system, are different from horizontal wells which are drilled from shoreline towards the seabed using the horizontal directional drilling method (Table 4). However, the flow path length from the sea to the wells and the hydraulic retention time might have more impact on the removal efficiency than geological site. Dehwah et al. [58] have shown that raw water quality, extracted from ten individual vertical beach wells along the Red Sea shoreline of Saudi Arabia, was highly improved compared with the raw seawater source as the wells aquifer matrix has removed 100% of algae concentrations and reduced the number of bacteria significantly.

7.3. Intake screens

In desalination facilities, screens, consider the first tier of pretreatment for both thermal and membrane desalination facilities, are used to prevent coarse objects, debris and large-diameter total suspended solids (TSS) from entering the intake pipelines. Open ocean intakes are generally equipped with coarse bar screens to prevent the marine organisms from entering the desalination plant followed by smaller-size (fine) screens to prevent debris from interfering with the downstream desalination plant treatment processes. Blooming species are usually in a size range (10–50 µm) and can easily pass through inlet screens and enter water desalination facilities [1]. Besides, microalgae, phytoplankton, cyanobacteria, and other organisms that feed on them may pose an impingement risk to desalination facilities by blocking or fouling the screen itself during

Table 4
Selected desalination plants with vertical wells as intake

Desalination plant	Location	Capacity (m^3/d)
Sur	Oman	160,000
Alicate (two facilities)	Spain	130,000
Tordera Blanes	Spain	128,000
Pembroke	Malta	120,000
Bajo Almanzora, Almeria	Spain	120,000
Bay of Palma Mallorca	Spain	89,600
WEB Aruba	Aruba	80,000
Lanzarote IV	Spain	60,000
Sureste Canary Islands	Spain	60,000
Blue Hills	Bahamas	54,600
Santa Cruz de Tenerife	Spain	50,000
Ghar Lapsi	Malta	45,000
Ċirkewwa	Malta	42,000
CR Aguilas, Murcia	Spain	41,600
SAWACO	Saudi Arabia	31,250
Dahab	Egypt	25,000
Turks and Caicos Water Company	Providenciales, Turks and Caicos Islands	23,260
Windsor Field	Bahamas	20,000
North Side Water Works	Grand Cayman	18,000
Ibiza	Spain	15,000
North Sound	Grand Cayman	12,000
Red Gate	Grand Cayman	10,000
Abel Castillo	Grand Cayman	9,000
Al-Birk	Saudi Arabia	5,100–8,700
Lower Valley	Grand Cayman	8,000
West Bay	Grand Cayman	7,000
Britannia	Britannia	5,400
Bar Bay	Tortola, B.V.I.	5,400
Morro Bay	California, USA	4,500
Ambergris Caye	Belize	3,600

Information based on Missimer et al. [52].

HAB events [7]. Accordingly, proper screen selection and sizing, especially in regions prone to HABs, will assure that there is sufficient flow capacity during a bloom event.

7.4. Dissolved air flotation

DAF system is a clarification process used to remove particles prior to conventional media filtration or microfiltration (MF)/ultrafiltration (UF) system. Low-density particles that can float, such as algal cells, oil and grease, which are not efficiently removed by sedimentation or filtration, can be separated using DAF pretreatment. Such a technology that precedes media filtration is proposed as the most effective technique to overcome the problems associated with algal blooms (reduce algal cell concentrations to a large extent; thus protecting media filters from rapid clogging, reduced capacity, and breakthrough) and may incorporate into facility designs as a preventative maintenance measure. Unlike sedimentation, DAF is more efficient in removing low-density particles from water; thus a proper treatment method for algal bloom-impacted waters (Table 5). The system is usually used in desalination plants that are prone to algal bloom events. Removal is achieved by mixing the feedwater with water that has been saturated with air under pressure and then releasing the air at atmospheric pressure inside a flotation tank. Upon releasing the pressurized water, a great number of micro-bubbles are formed and adhere to coagulated flocs and suspended matter making them float to the surface (Fig. 11).

In late 2008, a severe persistent red tide incident occurred along the UAE coast. Throughout the HAB, many desalination facilities were forced to shutdown, including Fujairah Fresh Water Company plant in Fujairah port, Al Ghalilah SWRO plant, Khor Fakkan SWRO plant, Sharjah Electricity and Water Authority's (SEWA), the Federal Electricity and Water Authority's (FEWA) and Abu Dhabi Water and Electricity Authority's (ADWEA) Fujairah 1 facility; however, a pilot facility equipped with advanced DAF technology continued to function efficiently at the Fujairah 2 facility, which was under construction nearby [7].

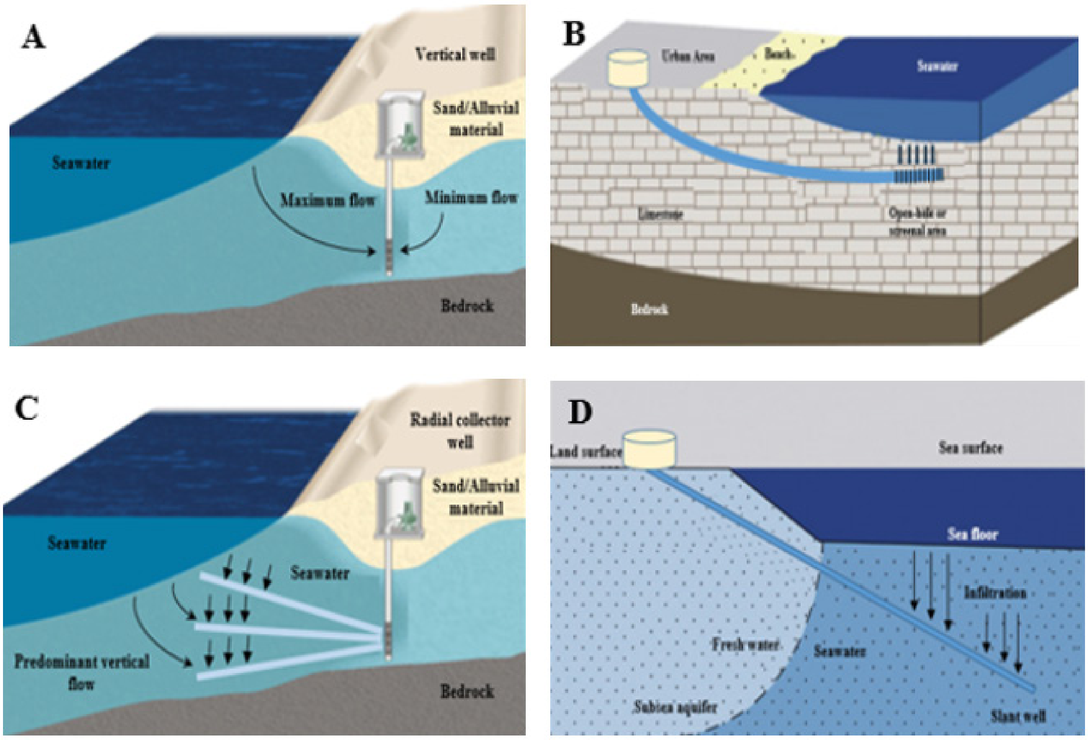

Fig. 9. Wells configurations: (A) vertical wells, (B) horizontal wells, (C) Ranney/collector wells, and (D) angle (slant) wells.

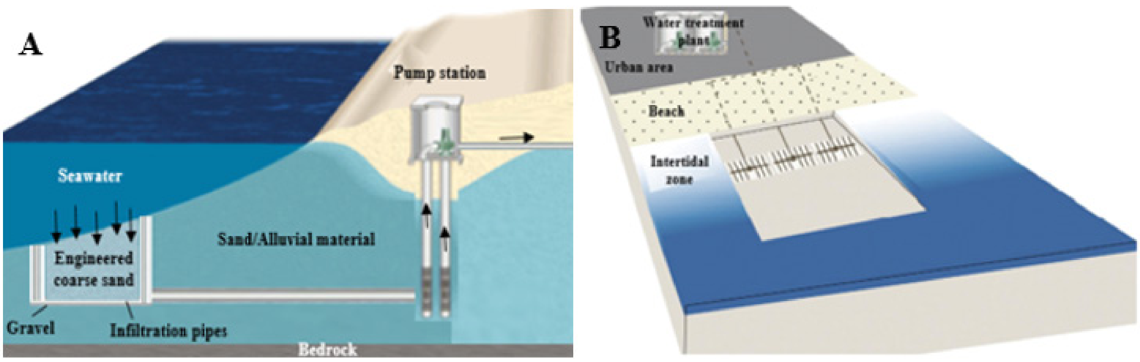

Fig. 10. Galleries configurations: (A) beach galleries and (B) seabed filters/galleries.

Following the commissioning of the Fujairah 2 plant, the advanced DAF system maintained production again during another severe red tide in 2011, which similar to the 2008 HAB event, caused many adjacent facilities to shutdown. In Kuwait, the combined DAF and UF pretreatment in the Al-Shuwaikh desalination plant helped to provide high raw water quality as SDI < 2.5 during good seawater conditions and SDI < 3.5 for deteriorated seawater conditions during the algal bloom [1].

7.5. Membrane filtration

Over the last decade, membrane filtration technology, including microfiltration (MF) and ultrafiltration (UF) has been examined and used at pilot and commercial scales as pretreatment for SWRO. They have many advantages over conventional methods, namely, lower footprint, consistent high permeate quality (in terms of SDI), higher retention of large molecular weight organics, lower overall chemical consumption and it efficiently removes TSS from seawater and thus protects the desalination facilities; however, it has been proven effective during HAB events (Table 5) [8,9]. Besides, the systems can eliminate the intracellular metabolites by size exclusion of the HAB cells and subsequent intracellular toxin removal [35]. At the Shuwaikh Seawater reverse osmosis (SWRO) desalination plant, the pretreatment configuration with a combination of dissolved air filtration (DAF) device and ultrafiltration (UF) membrane modules have proven to function adequately during the red tide event in 2012 [59]. Guastalli

Table 5
The capability of subsurface intake systems, dissolved air flotation and membrane filtration in removing algae, biopolymer and TEPs

Treatment type	Water source	Algal organic matters removal capability %	References
Subsurface intake/Galleries/Seabed gallery	West Mediterranean Sea	Biopolymers 75%	Rodriguez [61]
Subsurface intake/Vertical beach wells	Oman Gulf	- Algae >99.9 - Biopolymers >85 - TEPs 62–70	Rachman et al. [55]
Subsurface intake/Vertical beach well	N. Atlantic (Turks and Caicos)	- Algae >99 - Biopolymers ~100 - TEPs 90–92	
Subsurface intake/Vertical beach well	Red Sea (Jeddah)	- Algae >99 - Biopolymers ~100 - TEPs 34–65	
Subsurface intake/Vertical beach well	West Mediterranean Sea	- Algae >99 - Biopolymers ~100 - TEPs 64–84	
Subsurface intake/Horizontal wells	West Mediterranean Sea	- Algae 77 - Biopolymers ~90 - TEPs 34	
Subsurface intake/Vertical beach wells	Red Sea (Jeddah)	- Algae >99 - Biopolymers >80 - TEPs 55–75	Dehwah et al. [58]
Subsurface intake/Vertical beach wells	Red Sea (Jeddah)	- Algae 100 - Biopolymers >90 - TEPs 44 – >90	Dehwah et al. [62]
Dissolved air flotation (DAF)	Algae-spiked freshwater	Algae 96	Teixeira and Rosa [63]
Dissolved air flotation (DAF)	Algal culture	Algae 98	Henderson et al. [64]
Dissolved air flotation (DAF)	Algae-spiked freshwater	Algae 90–100	Teixeira et al. [65]
Dissolved air flotation (DAF)	West Mediterranean Sea	Algae 75	Guastalli et al. [60]
Dissolved air flotation (DAF)	Algal culture (saline water)	Algae >90	Zhu et al. [66]
Dissolved air flotation (DAF)	River water (Meuse)	- Biopolymers >70 - TEPs >70	Villacorte [67]
Dissolved air flotation (DAF)	Lake water	Algae 96	Vlaški [68]
Membrane filtration/Microfiltration (MF)	Algal cultures	Algae >99	Castaing et al. [69]
Membrane filtration/Ultrafiltration	Algae-spiked freshwater	Algae 100	Zhang et al. [70]
Membrane filtration/Ultrafiltration	West Mediterranean Sea	Algae 99	Guastalli et al. [60]

et al. [60] have shown UF membranes were capable of removing suspended solids effectively, including algae (100% removal) and a large fraction of the bacterial contents.

7.6. Harmful algal bloom mitigation with clay

One promising control strategy is the rapid sedimentation of HABs to remove algal cells by dispersing clay over the water surface [22]. Ecologically inert clays have been shown to flocculate, sediment, and thus mitigate harmful algal blooms (Fig. 12) [71]. Under laboratory conditions, Philippine clay minerals showed their ability to remove efficiently phytoplankton cells physically [72]. Also, toxic dinoflagellate, *Karenia brevis*, and the potent neurotoxins (brevetoxins) produced by such species were removed effectively using the phosphatic clay, suggesting that the utility of natural clay as a means of reducing adverse effects from HABs, including removal of dissolved toxins in the water column [73]. As shown in Table 6, flocculation by clay can significantly help in reducing red-tide cells and their toxins.

7.7. Chromatographic and mass spectrometry techniques

Several analytical techniques combining chromatographic and mass spectrometry techniques (e.g., liquid chromatography-mass spectrometry-LC-MS) have been developed and further modified to monitor the concentrations of all the major HAB toxins in the aquatic environment [22]. In Lake Albano, LC-MS/MS (liquid chromatography—tandem mass spectrometry) was used to monitor the occurrence and abundance of cyanotoxins, such as microcystins and cylindrospermopsin over four months (Sept-Dec 2004) by analyzing water samples collected monthly

Table 6
Controlling harmful algal blooms through clay flocculation

Treatment type	Algal species	Treatment	Removal efficiency %	References
Phosphatic clay IMC-P	*Heterocapsa triquetra* (dinoflagellates)	Phosphatic clay IMC-P (1.8 µm mean equivalent spherical diameter, ESD)	Cells 100 (48 h by IMC-P in a low-flow (<2 cm s^{-1}) regime)	Archambault et al. [74]
Phosphatic clay	*Karenia brevis* (dinoflagellates)	Aqueous slurry of 0.75 g clay to 3 L of *Karenia brevis* culture	- Toxins >97 (after 4 h) - Toxins >90 (after 24 h) - Cells >85 (after 24 h)	Pierce et al. [73]
Mineral colloid and puregel/montmorillonite modified clay	*Prymnesium parvum* (haptophyte)	Mineral colloid (SPC-MC at 0.25 g/L) and puregel/montmorillonite (MI-PG at 0.50 g/L)	Cells 55	Sengco and Anderson [75]
Chitosan-modified clays		0.025 g/L chitosan-modified local soils	Cells 99 (Taihu Lake)	Pan et al. [76]
Xanthan and calcium hydroxide modified clay	*Amphidinium carterae* (dinoflagellates)	300 mg/L clays – 20 mg/L xanthan and 100 mg/L calcium hydroxide	- Cells 83–89 (within 30 min) - Cells 95–98 (after several hours)	Chen and Pan [77]
Moringa oleifera coagulant (MO) modified sand	*Amphidinium carterae* *Chlorella* sp. *Microcystis aeruginosa*	Sand was modified by MO alone	- Cells 80% (*Amphidinium carterae*) in seawater - Cells 20% (*Chlorella* sp.) in seawater - Cells 60% (*Microcystis aeruginosa*) in fresh water	Li and Pan [78]
	Amphidinium carterae *Chlorella* sp. *Microcystis aeruginosa*	Sand was modified by MO and chitosan	- Cells 96% (*Amphidinium carterae*) in seawater - Cells 96% (*Chlorella* sp.) in seawater - Cells 90% (*Microcystis aeruginosa*) in fresh water	
Bentonite-type clays		Aqueous slurry of clay (1.5 g/L), pH 9	Toxins 100	Seger et al. [79]
Lanthanum-modified bentonite clay (Phoslock™)	*Prymnesium parvum* (haptophyte)	Aqueous slurry of clay (1.5 g/L), pH 7–9	- Toxins 60–100 - Cells ≥80	Seger et al. [79]
Aluminum chloride modified clay	*Aureococcus anophagefferens* (pelagophyte)	Aqueous slurry of clay (0.25 g/L), pH 7–11	Toxins 70	Liu et al. [80]
Aluminum sulfate modified clay	*Aureococcus anophagefferens* (pelagophyte)	Aqueous slurry of clay (0.25 g/L), pH 7–11	Toxins 70	Liu et al. [80]
Polyaluminum chloride modified clay	*Aureococcus anophagefferens* (pelagophyte)	Aqueous slurry of clay (0.25 g/L), pH > 5	Toxins 75	Liu et al. [80]
Sulfuric acid modified clay	*Microcystis aeruginosa*	1 g/L of a PRC-D clay type (treated with 1.5 v/w sulfuric acid)	- Cells >87.3 - Microalgae 77.6 (at a local algae bloomed lake)	Kim et al. [81]
Chitosan-DMDAAC modified clay		Reacting chitosan with dimethyl diallyl ammonium chloride (DMDAAC) under microwave	Cells 99	Jin et al. [82]
Polyaluminum chloride modified clay (kaolinite)	*Alexandrium pacificum* (dinoflagellates)	Clay was modified by polyaluminum chloride (PACl, analytical reagent) at a ratio of 1:5 in hyper-pure water to produce a stock solution of 50.0 g/L and 0.6 g/L MC treatment	Cells 90% (vegetative cells)	Zhang et al. [83]

at the center of the lake and at different depths (from 0 to –30 m) [84]. In the same vein, Hartnell et al. [85] have also measured microcystins using liquid chromatography coupled to tandem mass spectrometry in two interconnected reservoirs varying in age and management regimes in southern Britain over 12 months. Such techniques might help in the rapid quality screening of the feedwater and product water samples for the presence of HAB toxins.

7.8. Molecular probes

Molecular methods used to detect organisms are usually faster and more accurate than traditional ones. Molecular probes have been developed for the fast detection and counting of many HAB species; however, these probes are often either antibodies or short segments of DNA that are specific for the HAB species of interest [22]. Oligonucleotide probes have been used to determine HAB species using short, synthetic DNA that selectively attaches to sequences specific to a target organism [86]. Quantitative polymerase chain reaction (qPCR) has promise as a valuable quantification tool in determining the blooming sources and establishing the proportion of toxic and non-toxic genotypes in harmful algal blooms and might help in promptly mitigating their economic, ecological, and environmental effects, including providing the timely warning of approaching HABs. However, improved ELISA (enzyme-linked immunosorbent assay)-based methods with lower detection limits for different toxins have become commercially available for both screening and routine monitoring purposes. In a shallow lake in Vancouver, WA, USA, quantitative polymerase chain reaction (qPCR) was shown to be useful in probing toxin-producing gene (mcyE) from cyanobacteria with low abundance, complementary to traditional methods with microscopical counts, ELISA and PCR results [87]. Such developed techniques will hold promise for

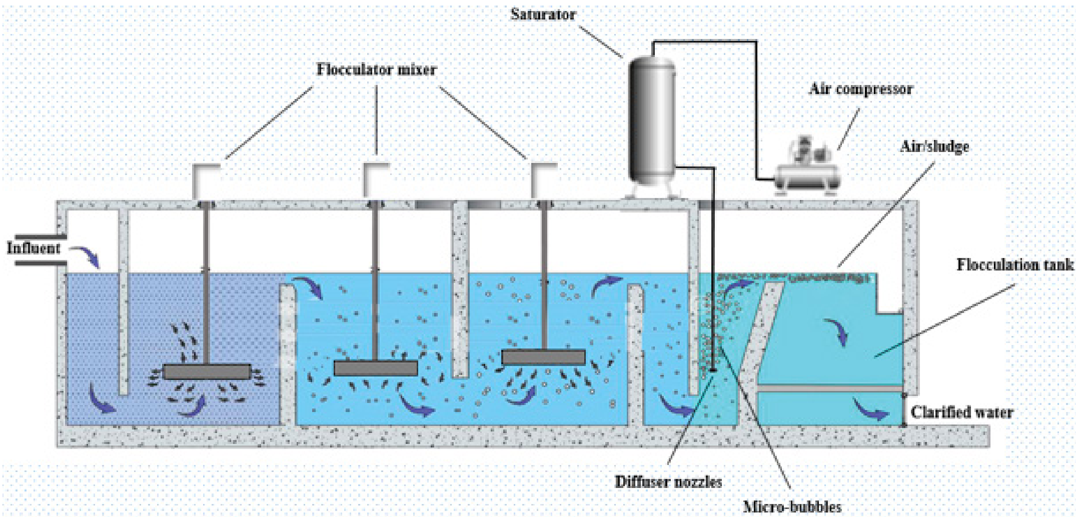

Fig. 11. Typical diagram for DAF system.

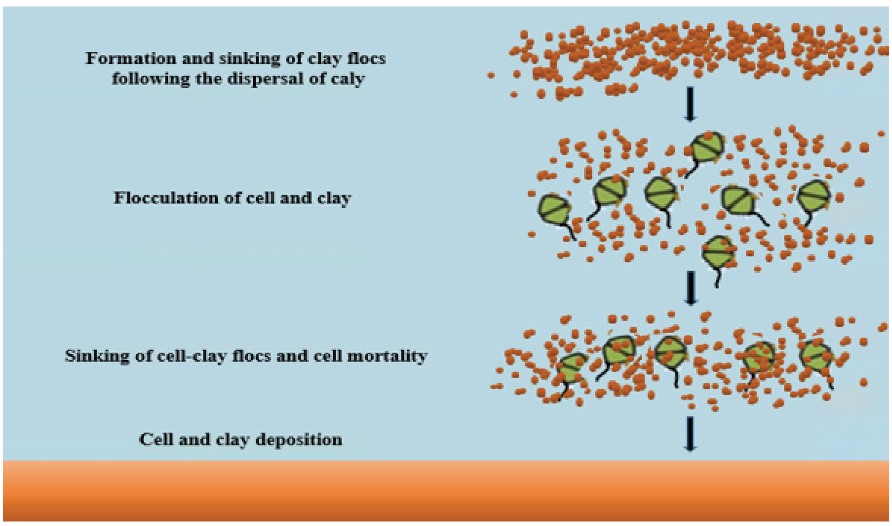

Fig. 12. Schematic diagram showing how the dispersal of clay slurry can lead to the flocculation of particles in seawater, and sedimentation of HAB cells.

earlier warning and regular monitoring to better control and protect coastal and marine resources from negative impacts by harmful algal blooms.

8. Conclusion

Rapid, large-scale growth of microscopic planktonic algae, named harmful algal blooms (HABs) have troubled many marine coastal regions around the world. During the last decades, the number of HABs, the type of resources affected, and the economic losses reported have all increased dramatically. Economic losses mainly influence the fishing and aquaculture industry, but recently the desalination industry has been increasingly affected as well. To ensure constant operation in seawater desalination plants prone to algal blooms, it is beneficial to use some of the monitoring techniques that can help in the detection and monitoring of the algal biomass and the red tide outbreaks. Furthermore, molecular-based methodologies will provide major development in the control measures of toxins and causative HABs in the future. However, the intake and/or the pretreatment system should also be reliable and robust to ensure continuous operation at design capacity and to minimize breakthroughs of red tide-forming algae and their growth products to the downstream desalination process.

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